Atmospheric Physics I

- 2e. Determine the variables associated with temperature and moisture.

Temperature

- Temperature is the degree of “hotness” or “coldness” as measured with a thermometer using some definite scale (scalar quantity)
- Units – degrees
- Temperature scales:
  - Fahrenheit (°F.)
  - Celsius (°C.)
  - Kelvin (K)

RELATIVE TEMPERATURE SCALES

	BOILING POINT	MELTING POINT
FAHRENHEIT (°F)	212	32
CELSIUS (°C)	100	0
KELVIN (°K)	373	273

Temperature

- Temperature gradient
  - Rate of change of temperature per unit distance (perpendicular to the isotherms). Can be horizontal or vertical.
  - Horizontal temperature gradient
    - TG = $\Delta T / \Delta n$
      - ΔT is the change in temperature
      - Δn is the distance perpendicular to the isotherms.
    - Temperature gradient is directly proportional to the change in temperature.
    - The temperature gradient vector is oriented along Δn and points in the direction of lower temperatures.

Temperature

- Temperature gradient
  - Review of gradient terminology
    - Tight or strong: temperature change is large, isotherms are closely spaced.
    - Loose or weak: temperature change is small, isotherms are widely spaced.

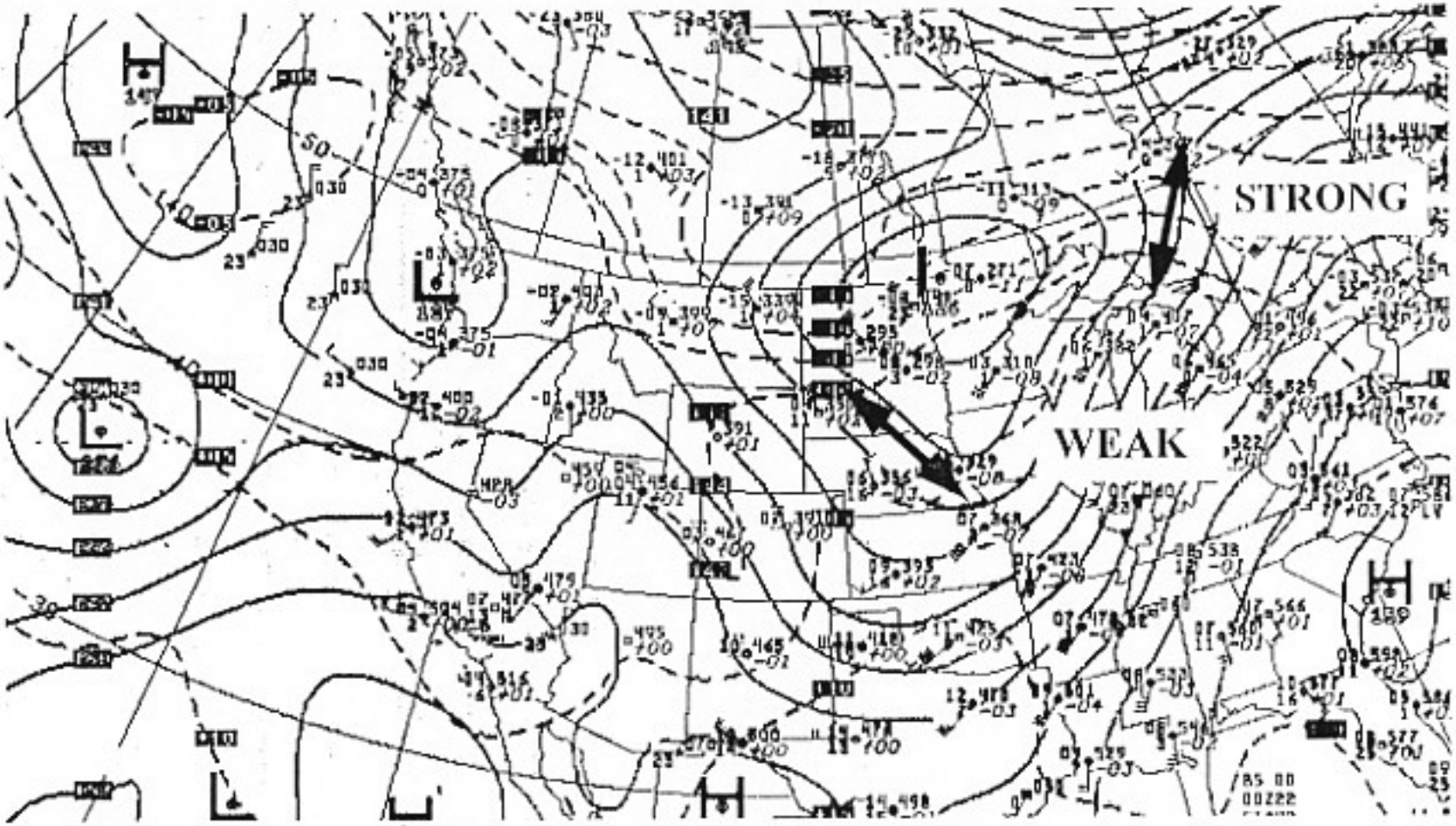
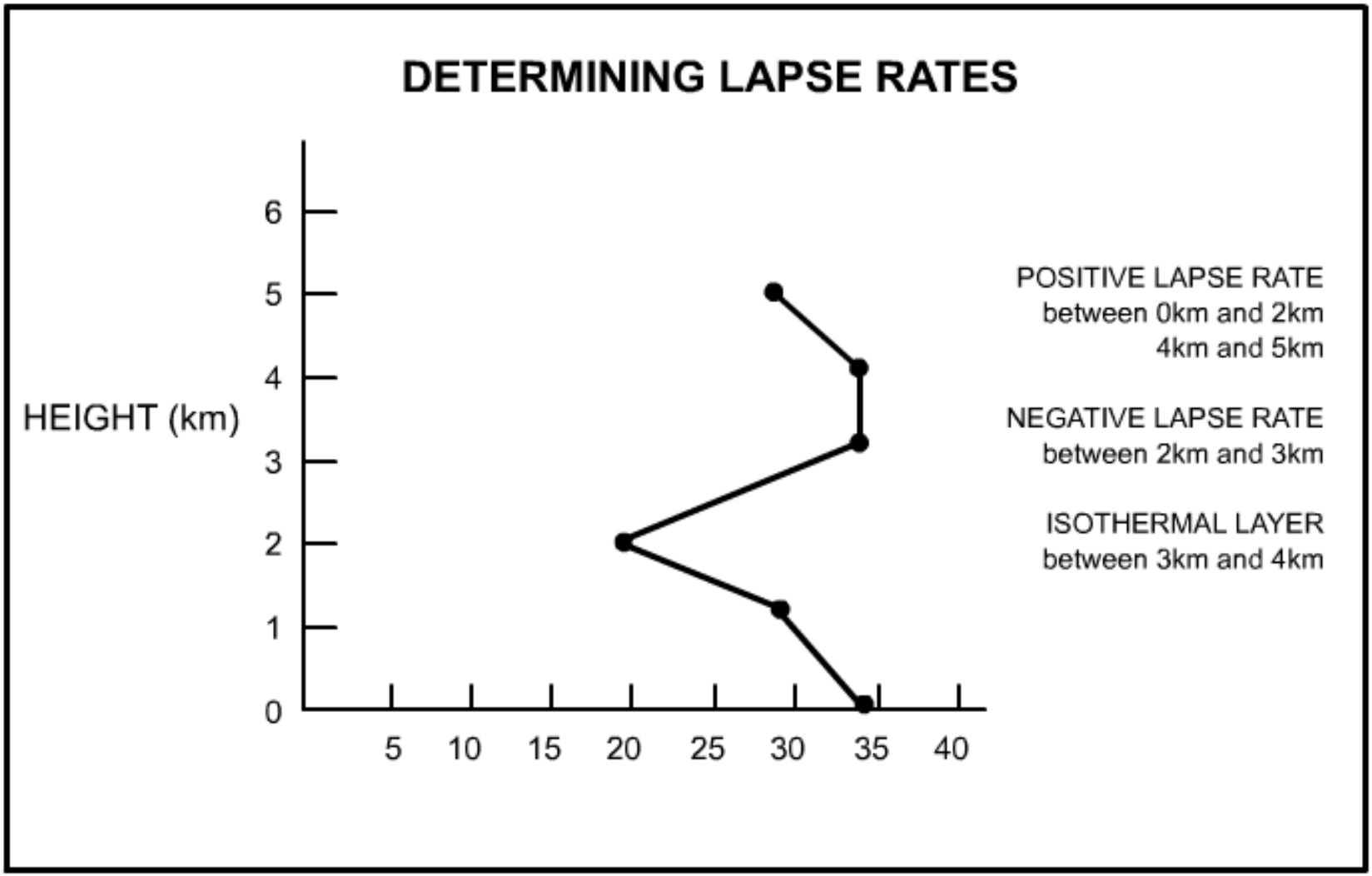


Figure 4-1 *Temperature Gradient on an 850mb Chart*

Temperature

- Lapse Rate (Vertical Temperature Gradient)
  - The rate of change in temperature with height. Symbolized by the Greek letter gamma (γ).
  - Equation: $\gamma = -\Delta T / \Delta z$
  - Units: °C/km
  - $\Delta T = T_{upper} - T_{lower}$
  - $\Delta z = z_{upper} - z_{lower}$


DETERMINING LAPSE RATES
HEIGHT (km)
0
1
2
3
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6
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35
40
POSITIVE LAPSE RATE
between 0km and 2km
4km and 5km
NEGATIVE LAPSE RATE
between 2km and 3km
ISOTHERMAL LAYER
between 3km and 4km

Temperature

- Lapse Rate (Vertical Temperature Gradient)
  - Lapse rate values:
    - Positive lapse rate – temperature decreases with height
    - Negative lapse rate – temperature increases with height (inversion)
    - Isothermal – temperature does not change with height
  - U.S. standard lapse rate = 6.5 °C/km (troposphere)

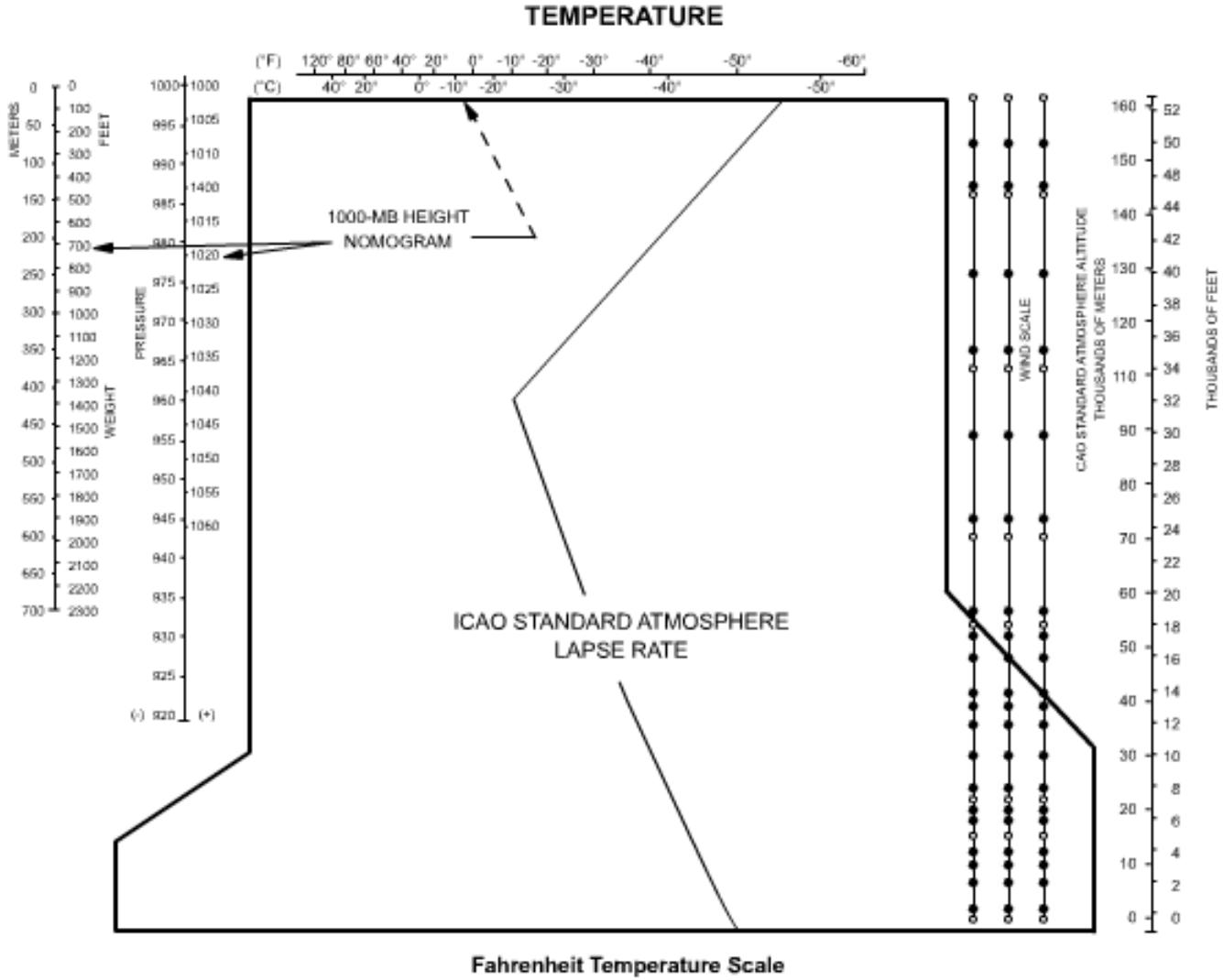
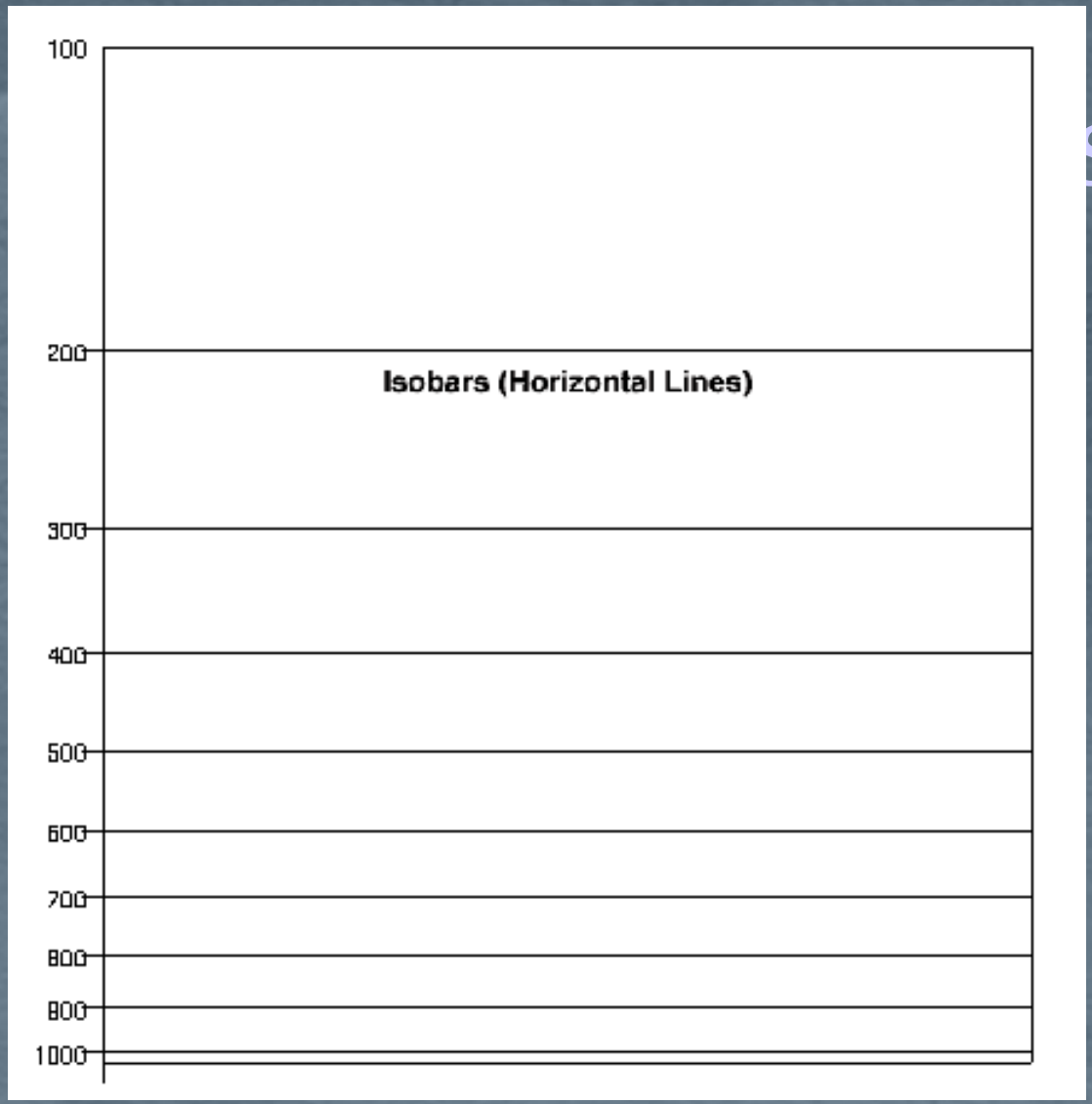


Figure 8. Auxiliary Scales on the Skew-T Chart

Skew-T overview

- Lines on the Skew-T
  - Isobars
    - Horizontal, solid brown lines logarithmically spaced at 10 mb intervals
    - Pressure levels are labeled every 50 mbs at both ends and the center of the line
    - The area from the 400 mb - 100 mb is also used for analyzing 100 mb – 25 mb.
    - The labels are in brackets at the end of the appropriate isobars.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Isobars (Horizontal Lines)

Skew-T overview

- Lines on the Skew-T
  - Isotherms (lines of equal temperature)
    - Straight, solid brown lines sloping from lower left to upper right (spacing is equal on entire chart)
    - Printed in 1 °C intervals.
    - Labeled in 5 °C intervals
    - Fahrenheit scale is printed along the bottom edge of the Skew-T

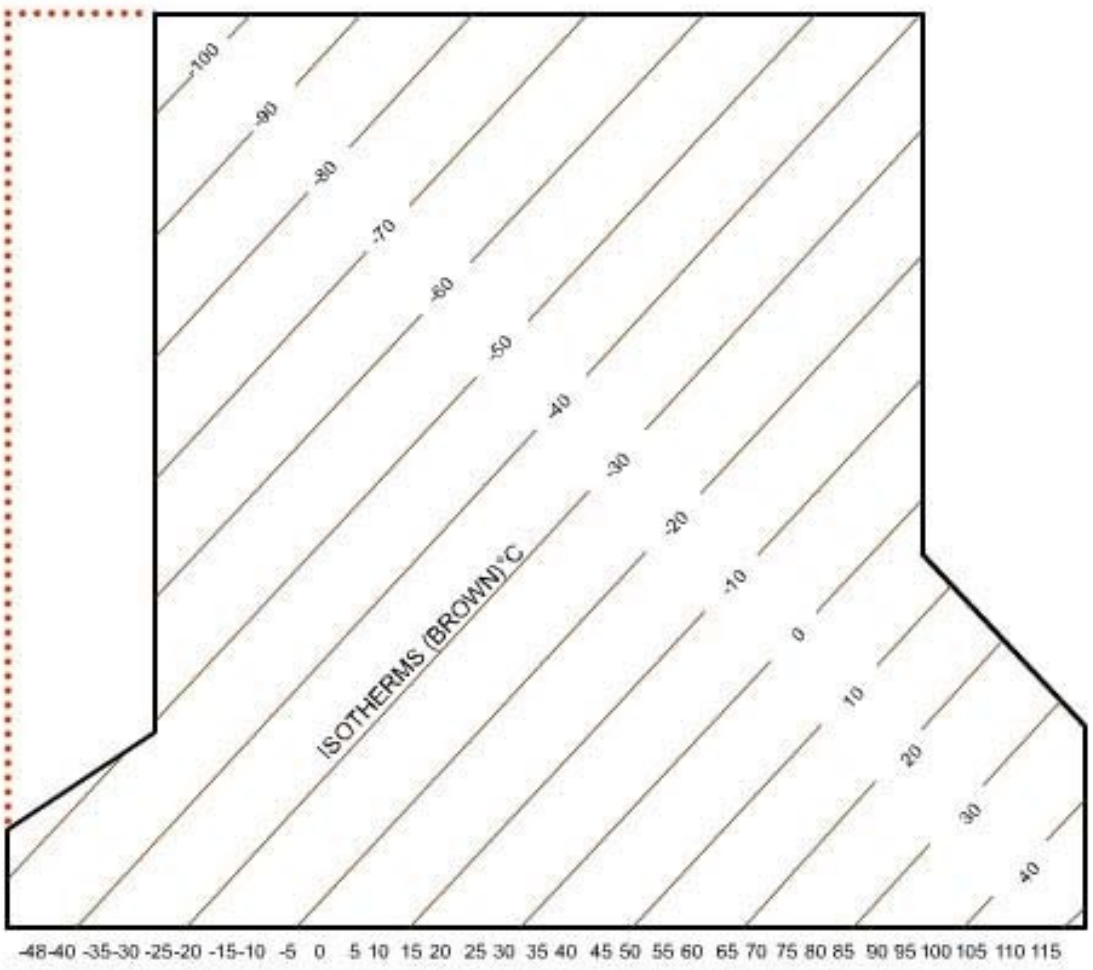
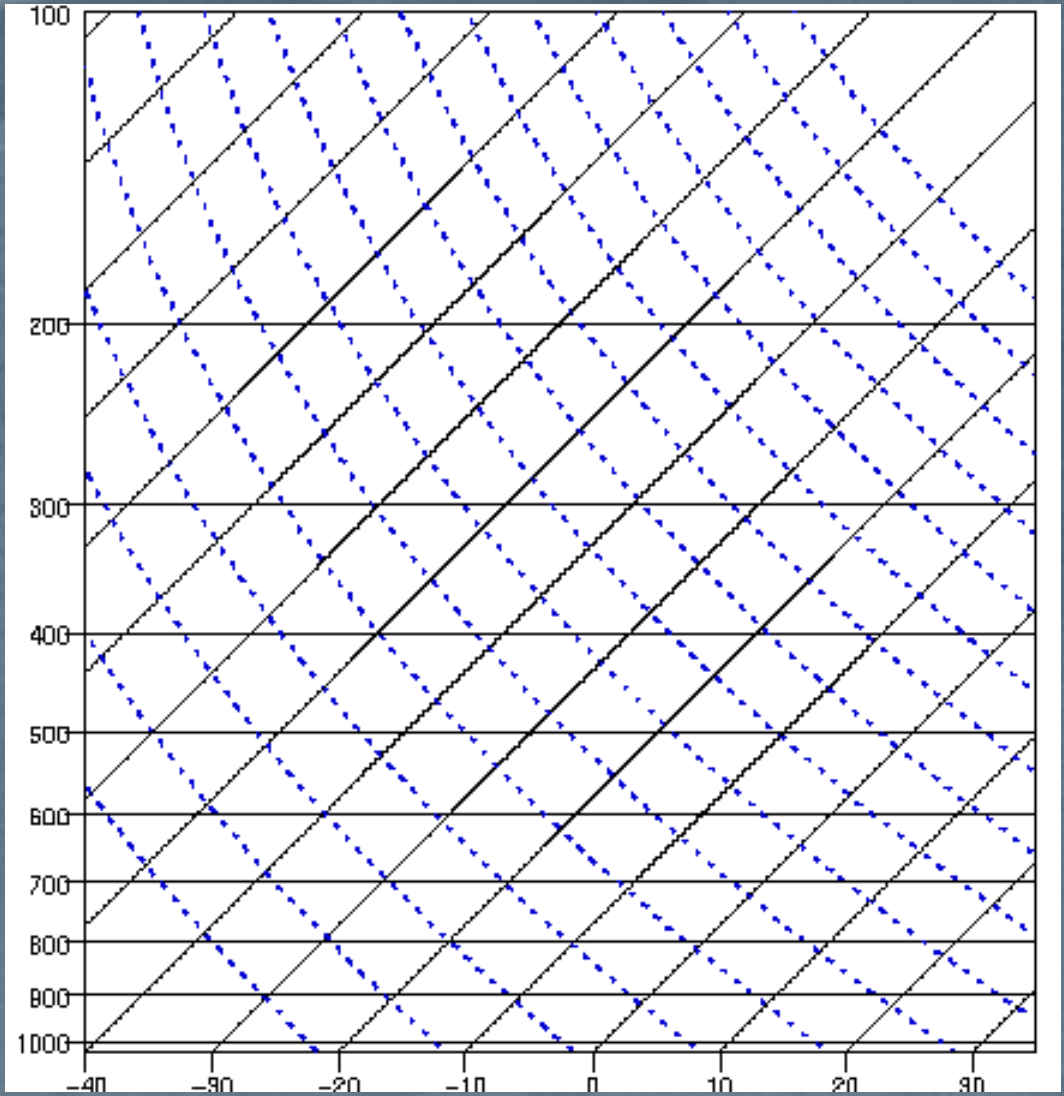


Figure 3. Isotherms on the Skew-T Chart

Skew-T overview

- Lines on the Skew-T
  - Dry adiabats (γ_d)
    - Also called potential temperature lines (gamma is used to represent lapse rate)
    - Slightly curved, solid brown lines sloping from lower right to upper left.
    - They represent the rate of change of a parcel of dry air rising or descending adiabatically (with no heat exchange between the parcel and the environment)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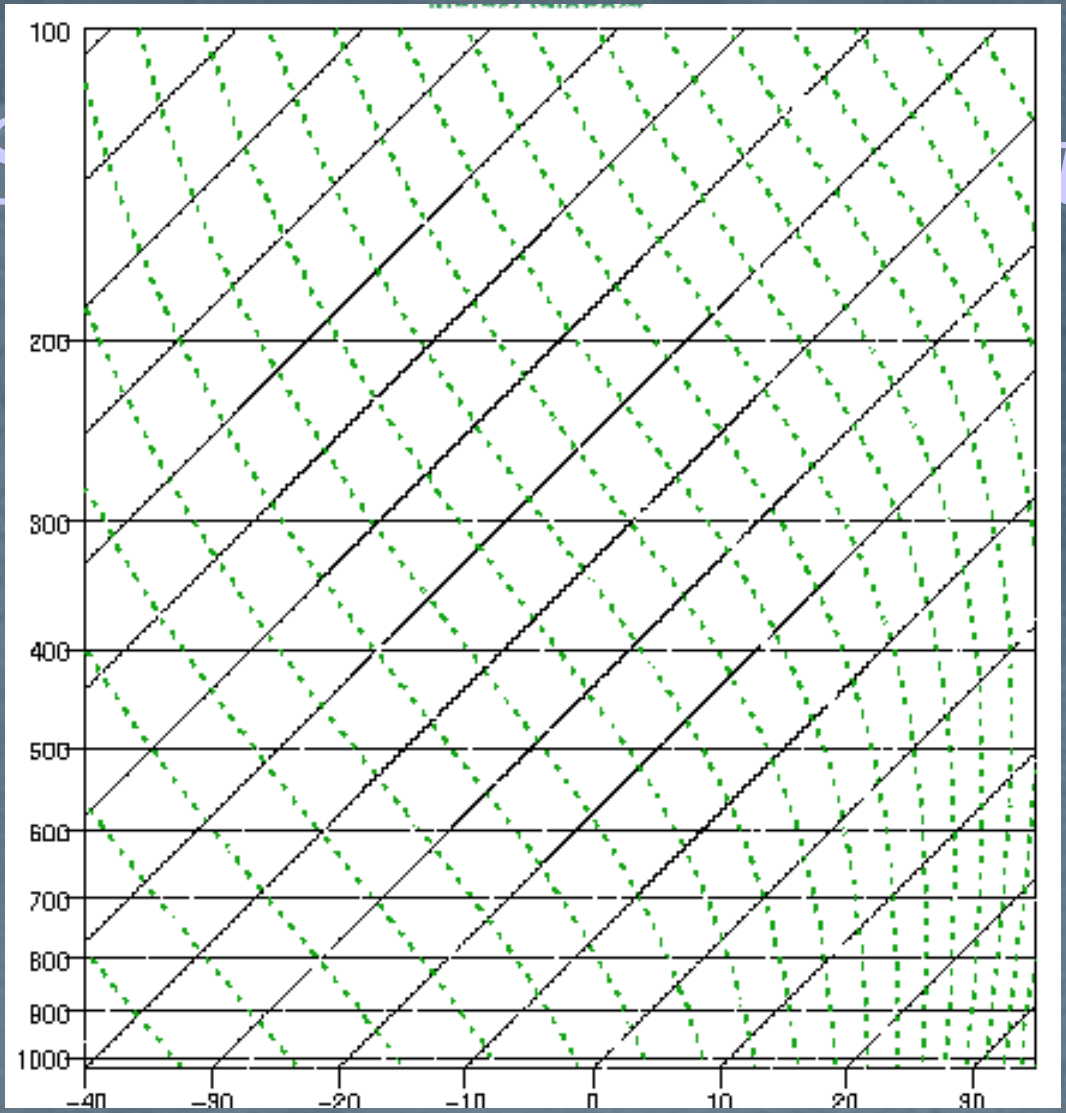
Skew-T overview

- Lines on the Skew-T
  - Dry adiabats (γ_d) cont.
    - Represents a lapse rate of approximately 10°C/km.
    - Printed at 2°C intervals.
    - Labeled every 10°C at 1030 mb and along the other edges of the chart.

Skew-T overview

- Lines on the Skew-T
  - Saturation adiabats (γ_m)
    - Slightly curved, solid green lines sloping from the lower right to upper left.
    - They represent the rate of change of temperature of a parcel of saturated air, rising or descending pseudo-adiabatically (all condensed water is assumed to fall out of the parcel).
    - The latent heat of condensation released causes the parcel to be warmer than with adiabatic lift.

S ts

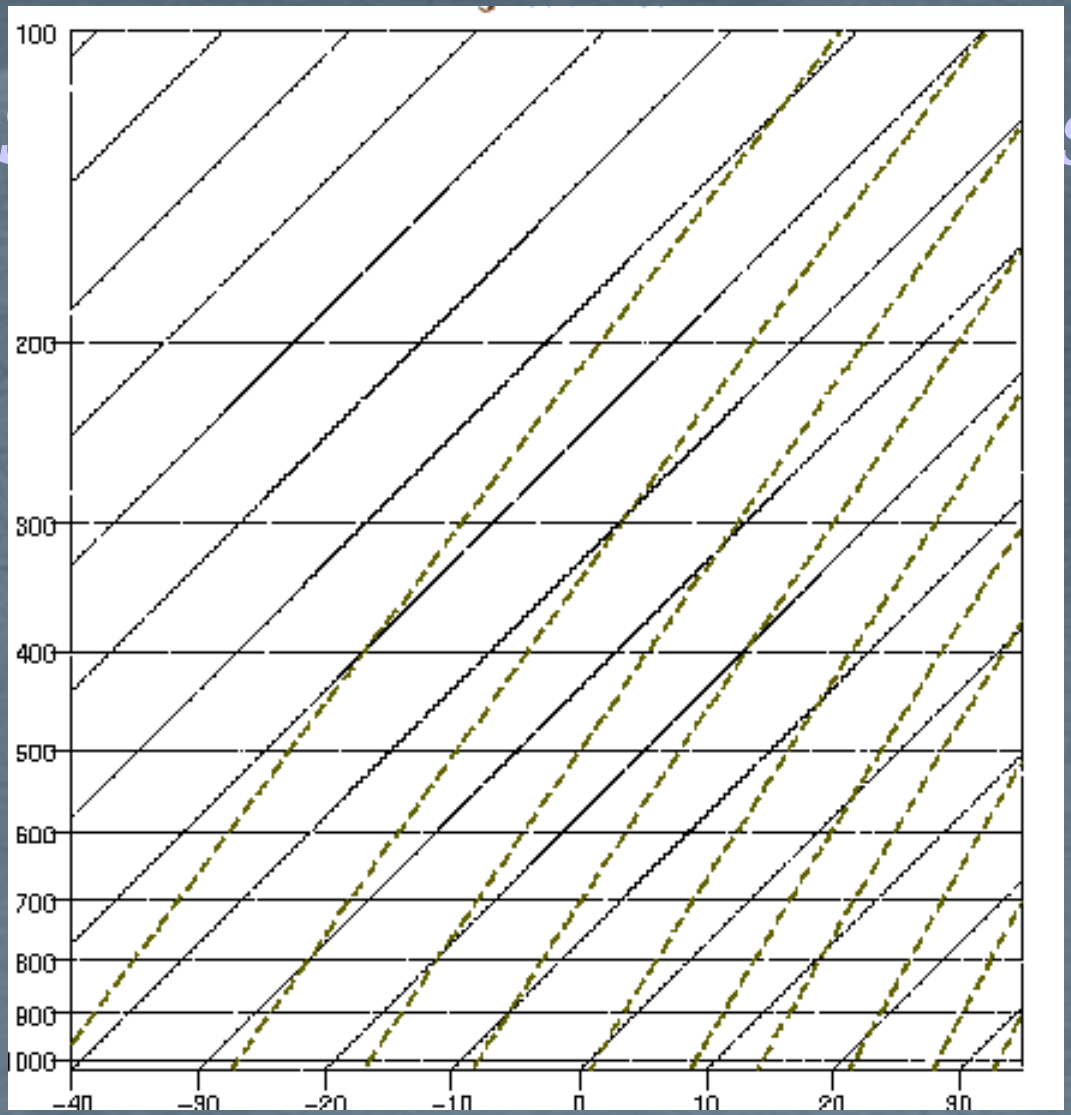


Skew-T overview

- Lines on the Skew-T
  - Saturation adiabats (γ_m) cont.
    - Printed in 2°C intervals.
    - Labeled every 2°C at 530 mb and 200 mb. (Tend to parallel the dry adiabats at cold temperature/low moisture content)

Skew-T overview

- Lines on the Skew-T
  - Saturation mixing ratio lines (w_s)
    - Slightly curved, ***dashed*** green lines sloping from lower left to upper right.
    - Represents ration of grams of water vapor per kilogram of dry air (parts of water vapor/1000 parts dry air – one of the best measurements of moisture)
    - Spacing of lines decreases as numerical value increases.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Skew-T overview

- Lines on the Skew-T
  - Saturation mixing ratio lines (w_s) cont
    - Labeled at 975 mb
    - Do not confuse with saturation adiabats

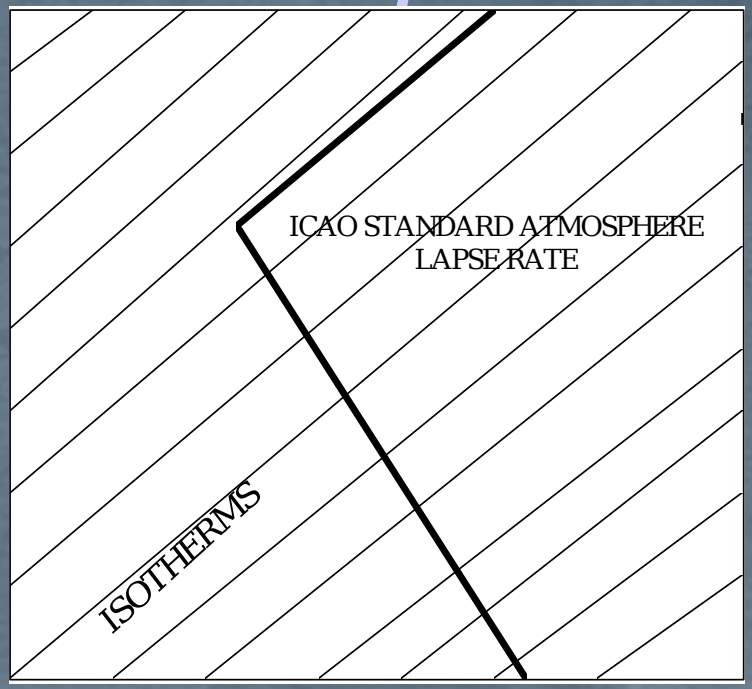
Skew-T overview

- Lines on the Skew-T
  - Thickness
    - The distance between two pressure levels
    - Dependent on temperature and moisture content

Skew-T overview

- Standard Atmosphere
  - The lapse rate is shown by a **heavy brown line** in the center of the chart starting at 1013 mb and 15°C.
  - It is used to compare the actual atmospheric conditions to standard atmosphere (AWS/TR-79/006 Para 2.8)

ICAO Standard Atmosphere



Skew-T (condensation levels)

- Condensation levels
  - Lifting Condensation Level (LCL)
    - The LCL is the height at which a parcel of air would become saturated if lifted dry adiabatically.
    - It is the point at which saturation would occur if parcel is lifted mechanically, orographic, frontal, etc.

Skew-T (condensation levels)

- Condensation levels
  - Convective Condensation Level (CCL)
    - The CCL is the height to which a parcel of air will rise, if heated from below, adiabatically until saturation occurs.
    - The potential cloud bases of cumuliform clouds if they are caused strictly by surface heating.
  - Convective temperature (T_c) – the temperature the surface must reach for convection to begin.

Skew-T (condensation levels)

- Condensation levels
  - Mixing Condensation Level (MCL)
    - The MCL is the lowest height in a layer mixed by turbulence, at which saturation occurs.
    - It is used for predicting cloud bases in areas of strong mechanical mixing.

Skew-T

- Inversions
  - General characteristics
    - Temperature normally decreases with altitude in the troposphere
    - Occasionally, soundings show layers where temperatures increase with height (negative lapse rate)

Skew-T (inversions)

- Inversions
  - General characteristics
    - This layer is called an inversion
      - Base of the inversion – the lowest point of a layer through which temperature increases with height
      - Top of the inversion – the highest point of a layer through which temperature increases with height

Skew-T (inversions)

- Types of inversions
  - Radiation (nocturnal) inversion – an inversion formed by the rapid cooling of air in contact with the surface.
    - Favorable conditions
      - Long nights or periods of low solar radiation (winter)
      - Clear skies which allow infrared (terrestrial) radiation to escape from the earth's surface to outer space

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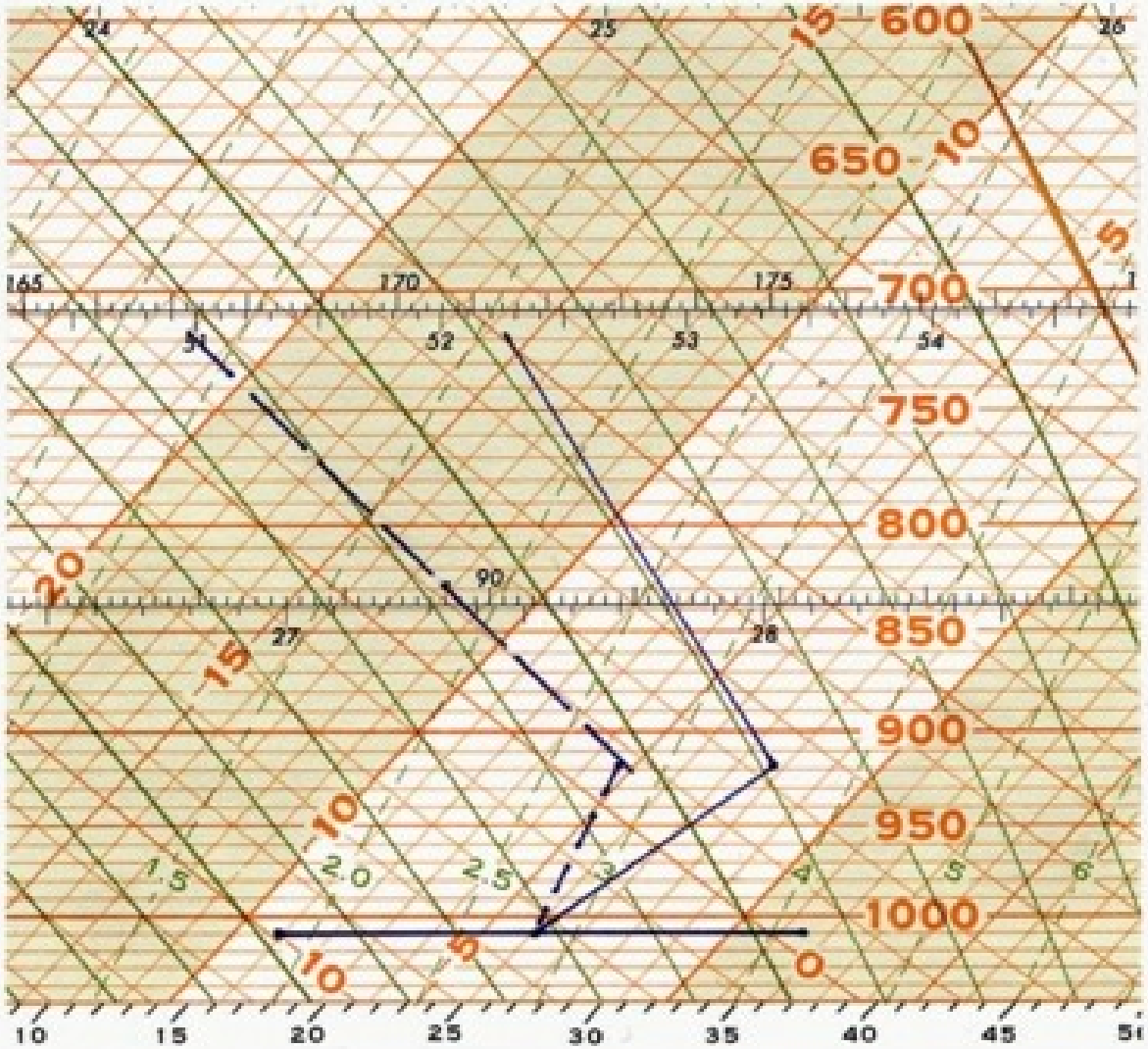
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Skew-T (inversions)

  - Dry air – water vapor would trap infrared radiation and reemits it back toward the earth thus preventing excessive cooling.
  - Light winds – limit low-level mixing of heat and moisture

- Atmospheric significance
  - Often associated with fog formation
  - Traps pollution which lowers visibility

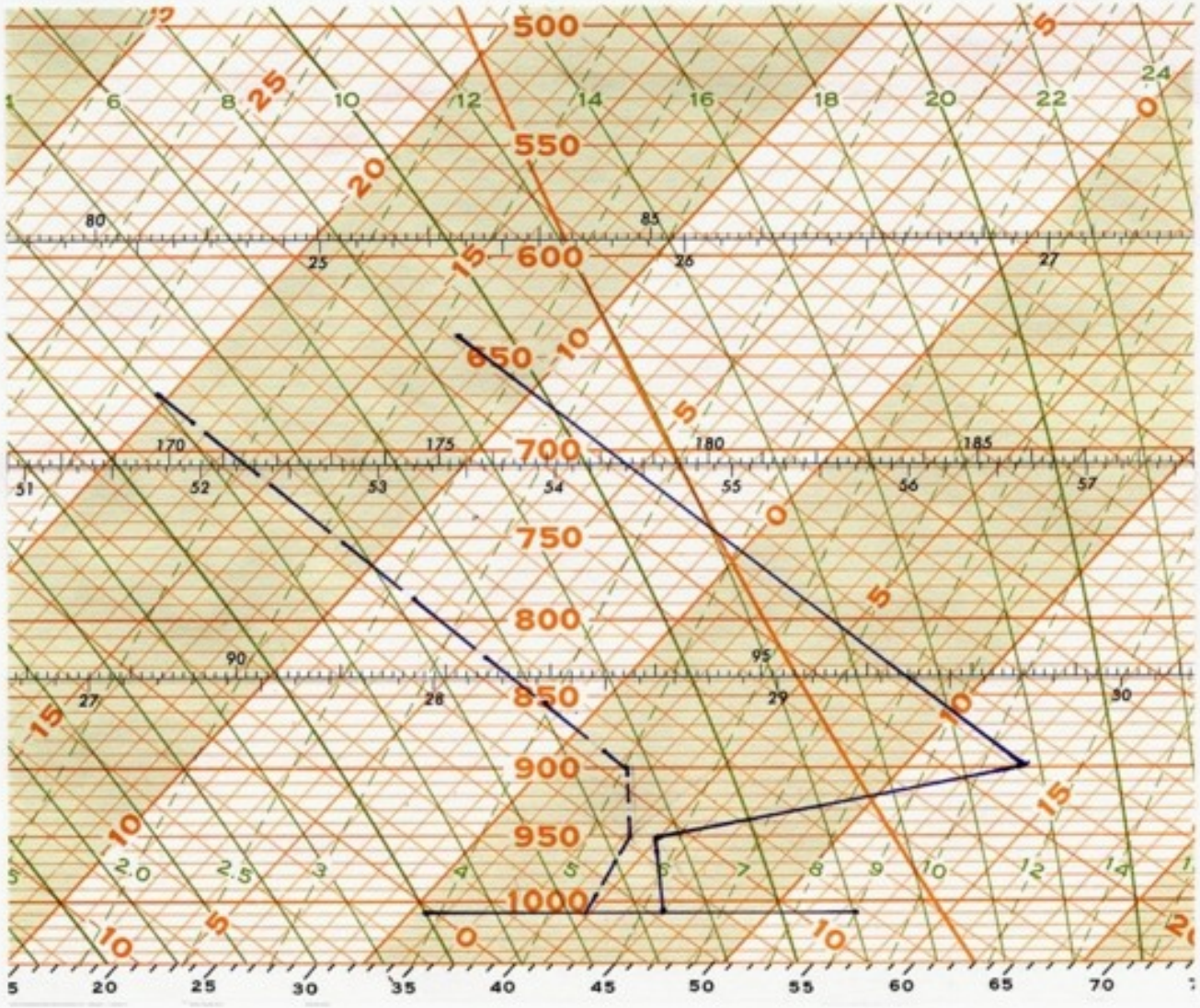
Skew-T (inversions)

- Identification
  - Surface based and vertically shallow (I.e., of small vertical extent)
  - T and T_d are closer or the same at the base of the inversion
  - Mixing ratio remains almost constant within the inversion layer
  - T_d decreases above inversion
  - Forms only at night, but may persist for a couple of hours past sunrise.

Skew-T (inversions)

- Subsidence inversion – a mechanically produced inversion formed by adiabatic warming or sinking of air
  - Favorable conditions for formation – high pressure systems
  - Atmospheric significance – Acts as a “lid” or “cap” and can dampen convective activity

T e

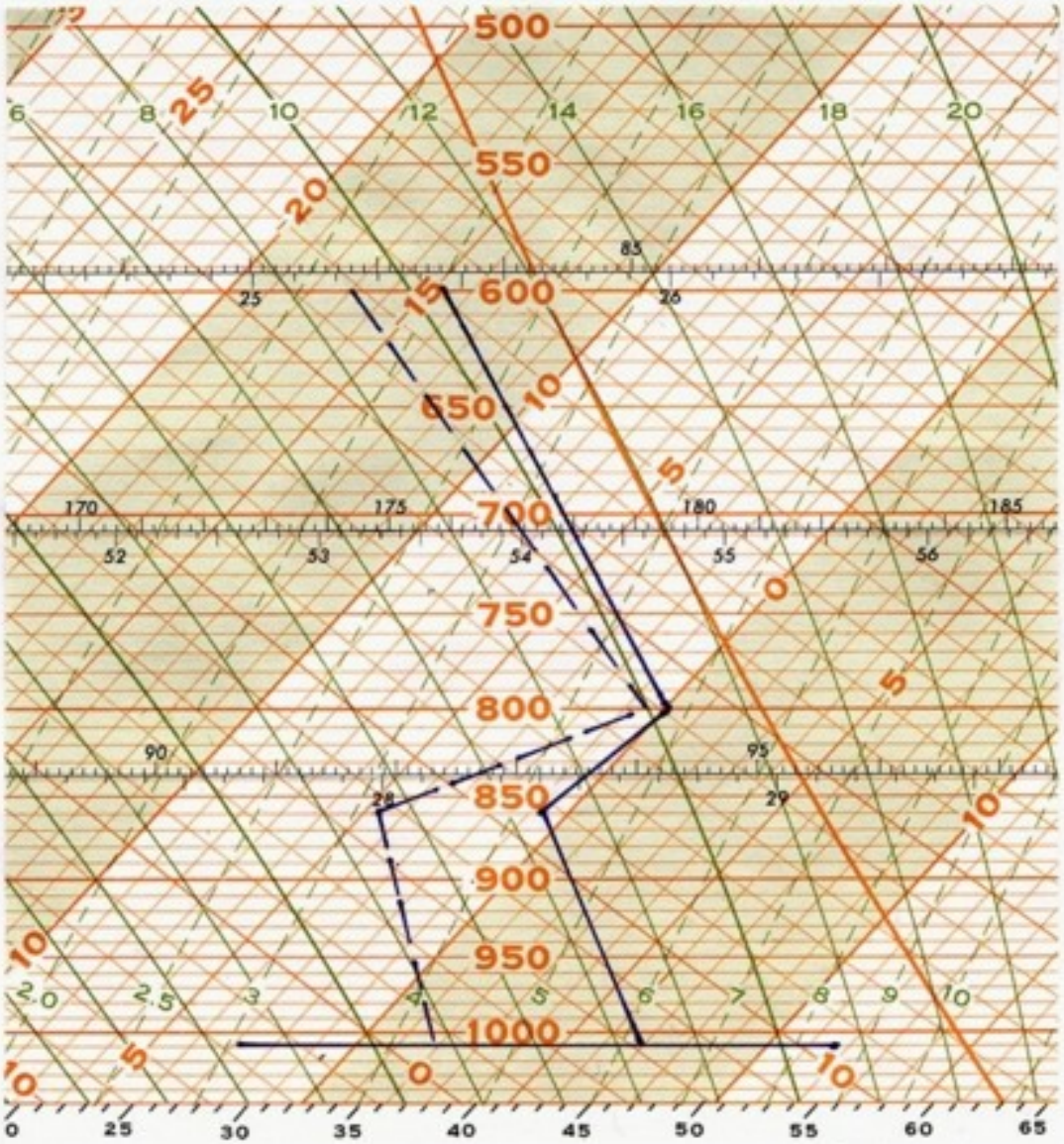


Skew-T (inversions)

- Subsidence inversion
  - Identification
    - T_d begins decreasing, often very rapidly, upward from the base of the inversion
    - Both T and T_d decrease rapidly (almost dry adiabatically) above the inversion

Skew-T (inversions)

- Frontal inversion (zone) – the transition zone between a cold air mass and the warmer air mass above it
  - Atmospheric significance – calculating frontal slope and intensity
    - Identification
      - T_d increases within the inversion
      - Winds change direction through the inversion
      - Usually of greater vertical extent than radiation inversions
      - Often are accompanied by cloudy skies
      - Present regardless of time of day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180
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56
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28
29
2.0
2.5
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4
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65

Skew-T overview

- Heat
  - Heat is a form of energy transferred between systems by virtue of their temperature differences.
  - Units: Joule (J) = Newton meter (N m). (calories are commonly used, 1 cal = 4.186 J).
  - Heat added to a system can raise the temperature or change the state of substances in the system.

Skew-T (heat)

- Two types of heat
  1. Sensible heat
     - It is heat that can be felt and measured with a thermometer
     - The sensible heat of a system can be changed by adding or removing heat, causing a change in temperature.

Skew-T (heat)

- Sensible heat (cont)
  - Equation: $Q = mC_p\Delta T$
    - Q = sensible heat added or removed
    - m = mass
    - C_p = specific heat – the amount of heat needed to raise the temperature of 1 gram of a substance 1°C

Skew-T (heat)

- Sensible heat (cont)
  - Equation: $Q = mC_p\Delta T$
    - Some Cp values:
      - Land .33 cal/g°C
      - Water 1 cal/g°C
      - Ice .56 cal/g°C
      - Water Vapor .44 cal/g°C

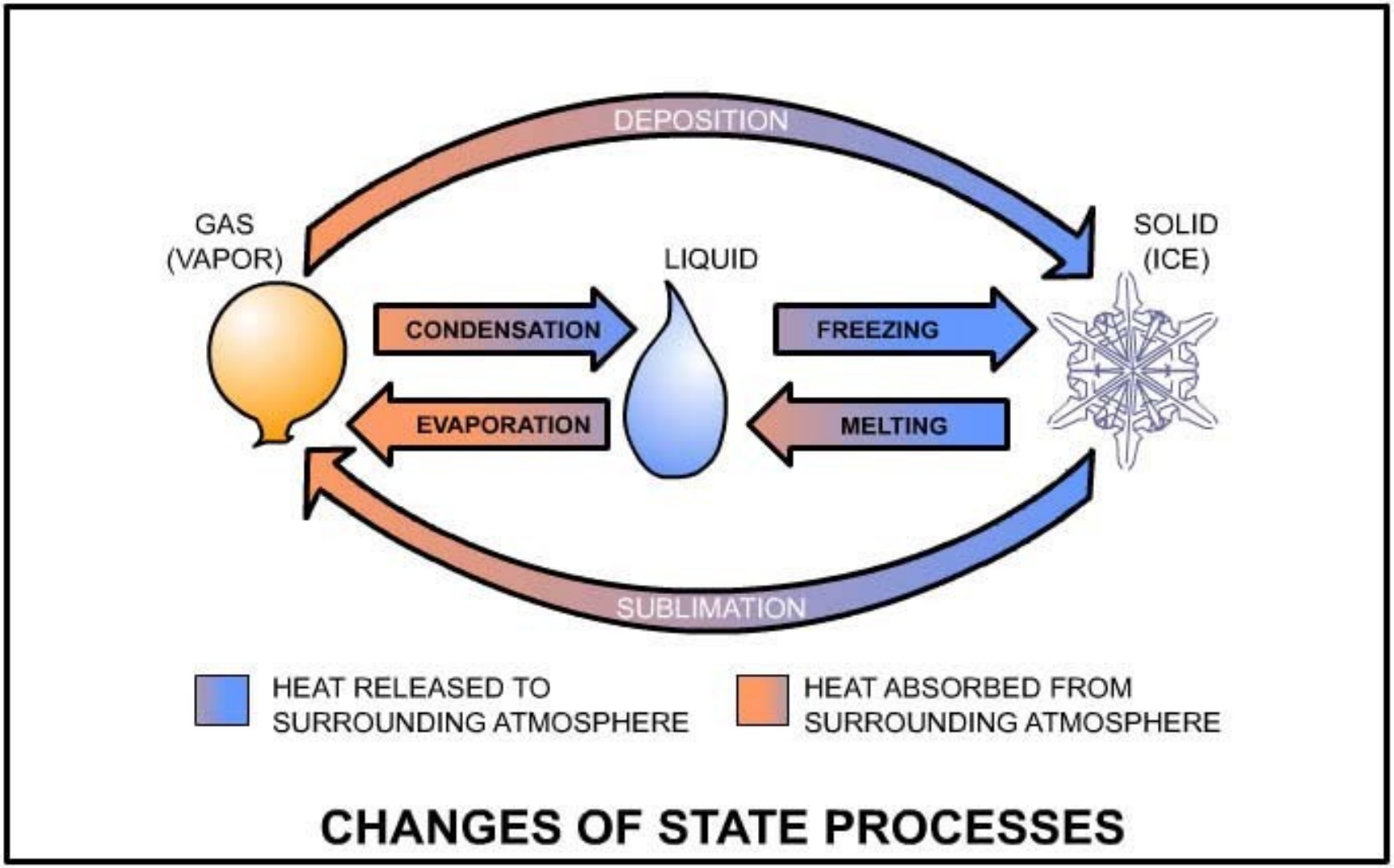
    $\forall \Delta T = T_{final} - T_{initial}$ (change in temperature)

Skew-T (heat)

- Sensible heat (cont)
  - Variable relationships
    - Heat is directly proportional to mass: ↑Q = ↑mCpΔT ↓Q = ↓mCpΔT
    - Heat is directly proportional to specific heat: ↓Q = m↓CpΔT ↑Q = m↑CpΔT
    - Heat is directly proportional to temperature change: ↑Q = mCp↑ΔT ↓Q = mCp↓ΔT
    - Temperature change is inversely proportional to specific heat: Q = m↓CpΔT↑ Q = m↑CpΔT↓
    - Water has a higher specific heat than land, so a given mass of water is slower to raise its temperature compared to an equal mass of land, when subjected to equal amounts of heat.

Skew-T (heat)

- Types of heat
  2. Latent heat
     - It is energy required to change a substance (in our case, water) form one state (phase) to another.
     - Types of phase changes
       - Changes which require heat. Energy is absorbed by the water molecules from the surrounding environment.
         - Melting – conversion from ice to liquid
         - Evaporation – conversion from liquid to vapor
         - Sublimation – conversion from ice directly to vapor


DEPOSITION
GAS
(VAPOR)
LIQUID
SOLID
(ICE)
CONDENSATION
FREEZING
EVAPORATION
MELTING
SUBLIMATION
HEAT RELEASED TO
SURROUNDING ATMOSPHERE
HEAT ABSORBED FROM
SURROUNDING ATMOSPHERE
CHANGES OF STATE PROCESSES

Skew-T (heat)

- Latent heat – types of phase changes (cont)
  - Changes which release heat. Energy is released by water molecules and can be used to heat the surrounding air.
    - Freezing – conversion from liquid to ice
    - Condensation – conversion from vapor to liquid
    - Deposition – conversion from vapor to ice

Skew-T (heat)

- Water can exist as a liquid at temperatures below 0°C and as a vapor at temperatures below 100°C.
- When water molecules undergo a phase change such as melting, evaporation, or sublimation, all the heat absorbed is used for the phase change.
  - The molecules are taken to a higher energy state.
  - None of this heat is used to change the sensible temperature.

Skew-T (heat)

- When ice is experiencing a phase change from solid to liquid, the liquid molecules remain at the same temperature as the solid form until all of the solid is gone.
- When water is experiencing a phase change from liquid to vapor (i.e., evaporation), the vapor molecules remain at the same temperature as the liquid form until all the liquid is gone.

Skew-T (heat)

- The release of latent heat will cause the molecules of water to return to a lower energy state.
- The released energy can be used to increase the temperature (sensible heat) of the surrounding air.

Skew-T (heat)

- When water molecules undergo a phase change such as freezing, condensation, or deposition, all the heat originally absorbed during the earlier melting, evaporation, or deposition process is now released during the phase change.
  - The molecules are taken to a lower energy state
  - The release of this heat will increase the sensible temperature of the substance

Skew-T (heat)

- Relative magnitudes of latent heat
  - Equation: Q = m L
    - Q is the latent heat either absorbed or released
    - M is the mass of water changing phase
    - L is the latent heat constant defined for each type of phase change
  - Units: Joule (J)

Skew-T (heat)

- Q is directly proportional to both mass and the latent heat constant.
  - The greater the mass, the greater the amount of latent heat involved.
  - The lower the latent heat constant, the lower the amount of latent heat involved.

Moisture parameters

- Moisture terminology
  - Dry air – contains absolutely NO water vapor
  - Moist air
    - Unsaturated – the air contains less water vapor than the maximum possible
    - Saturated – The air contains the maximum amount of water vapor possible, saturation is a state of equilibrium.

Moisture parameters

- Moist air (cont)
  - Saturated (cont)
    - The amount of water vapor in the air is constant, but water molecules are continuously being evaporated and condensed.
    - To maintain a saturated atmosphere, for every molecule of water evaporated, one is simultaneously condensed.

Moisture parameters

- Types of moisture variables
  - Absolute humidity
    - Density of the water vapor
    - Higher absolute humidity degrades contrast between target and background for infrared sensors.
  - Relative humidity (RH)
    - RH is the ratio of the actual amount of water vapor to the saturation value.
    - Units: %

Moisture parameters

- If the actual amount of water vapor in the air is held constant, the RH is inversely proportional to the temperature (I.e. the higher the temperature the lower the RH, and the lower the temperature, the higher the RH)

Moisture parameters

- Types of moisture variables
  - Dew Point Temperature (T_d)
    - The temperature at which saturation will occur when air is cooled at a **constant pressure** and with no change in moisture content.
    - Dependent only upon the amount of water vapor in the air
    - Units: degrees
    - If the temperature and the dew point are the same, then saturation occurs and the RH = 100%

Moisture parameters

- Types of moisture variables
  - Dew Point Depression ($T - T_d$)
    - Dew point depression is the number of degrees the dew point temperature is below the actual temperature.
    - Measures how close the atmosphere is to saturation.
    - Small values indicate air is close to saturation (high relative humidity)
    - Large values indicate the air is further from saturation (low relative humidity).
    - Units: degrees

Moisture parameters

- Types of moisture variables
  - Wet bulb Temperature (T_w)
    - Temperature to which air is cooled by evaporating water into the air until saturation occurs.
    - Always between the dew point and dry-bulb temperature.

Moisture parameters

- Types of moisture variables
  - Specific Humidity (q) – the ratio of the mass of water vapor to the total mass of air.
    - A reliable measure of the actual amount of moisture content in the air.
    - Units: grams/kilograms (dimensionless)
    - The higher the specific humidity, the higher the air's water vapor content

Moisture parameters

- Mixing Ratio (w) – the ratio of the mass of water vapor to the total mass of dry air.
  - A reliable measure of of the actual moisture content in the air.
  - Units: grams/kilograms (dimensionless)
  - The higher the mixing ratio, the higher the air's water vapor content.

Moisture parameters

- Vapor Pressure (e) – the pressure exerted by water vapor in the air.
  - A reliable measure of the actual moisture content in the air.
  - Units: millibars
  - Vapor pressure is actually a “partial pressure” of the total atmospheric pressure in a column of air
    - Example: the total atmospheric pressure in a column may be 1000 mb , where 10 mb of this 1000 mb is produced by the weight of water vapor, and the remaining 990 mb is produced by all the other gasses in the atmospheric column.
  - The higher the vapor pressure, the higher the air’s water vapor content.

Moisture parameters

- Virtual Temperature (T_v) – the temperature that dry air would have if it were the same density as moist air.
  - **Moist air is less dense than dry air.** The virtual temperature is always greater than the actual temperature.
  - Equation: $T_v = T + w/6$, where T must be in °C and w must be in g/kg (this is an empirical formula, so units do not work out)
    - **T_v is directly proportional to T**
    - **T_v is directly proportional to one sixth of w. T has a larger effect on Tv than w does.**

Adiabatic processes

- It assumes no heat or mass is exchanged between a system (a parcel of air) and its surroundings. (“laboratory” conditions)
- Used to discuss expansion and compression of air parcels (more in later objective).
  - A lifted parcel will expand and cool as the environmental pressure decreases.
  - A sinking parcel will compress and warm as the environmental pressure increases.

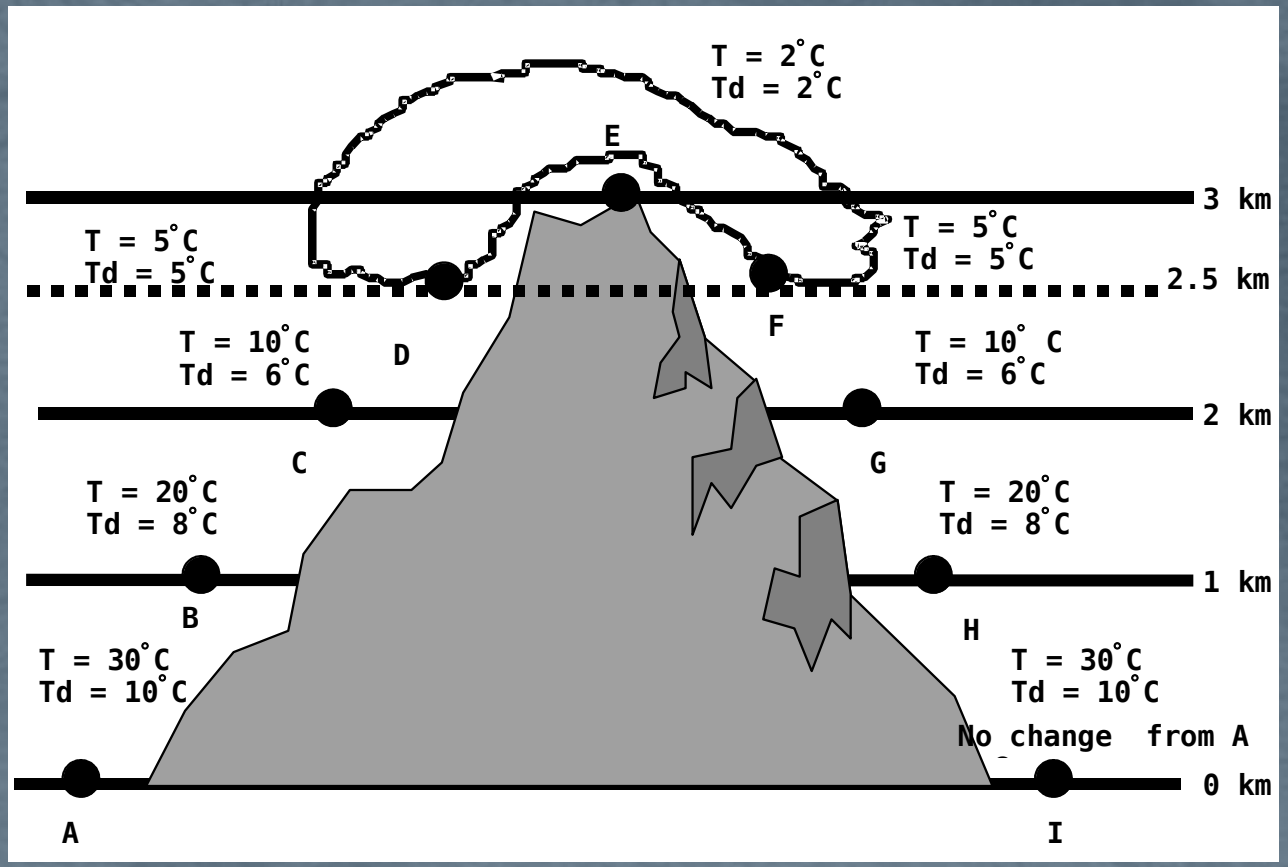
Adiabatic processes

- In a true adiabatic process, any condensed water/deposited ice produced during lift remains in the parcel. Any latent heat released remains in the parcel.

Adiabatic processes

- The process is REVERSIBLE. A lifted or sinking parcel returned to its original position will have its original temperature and dew point.
  - Any condensed water will evaporate, increasing water vapor content (dew point) to its original magnitude.
  - Any deposited ice will sublimate, increasing water vapor content (dew point) to its original magnitude.

Adiabatic Process



Adiabatic processes

- The amount of cooling/warming occurring during vertical movement depends upon whether or not the air is saturated.
  - Dry adiabatic rate (unsaturated air)
    - The temperature of a parcel will change 9.8 °C per km of altitude change. For practical purposes, we will use 10 °C per km.
    - As the air cools, the temperature approaches the dew point.
    - Once the parcel is saturated, the air no longer cools at the dry adiabatic rate.

Adiabatic processes

- Saturation (moist) adiabatic rate (saturated air)
  - Condensation and thus latent heat release occurs as air is lifted and further cooled.
  - Latent heat released during condensation acts to partially offset or retard the cooling of the parcel.
  - Therefore the temperature of the saturated air decreases less quickly than with unsaturated air.
  - The rate of cooling is not constant but averages 6 °C per km and approaches the dry adiabatic rate at cold temperature (low moisture contents). For extremely warm saturated air, the cooling rate may be as low as 3°C per km.

Adiabatic processes

- Dew Point Lapse Rate
  - The dew point is derived from the pressure exerted by water vapor molecules in the atmosphere. This "partial pressure exerted by water vapor changes as atmospheric pressure changes. Thus, as a parcel rises and experiences lower pressure, the partial pressure of water vapor decreases, thus forcing a 2°C per km reduction in dew point.
  - This process also works in reverse for subsiding air. For example, as a parcel sinks and experiences higher pressure, the partial pressure of water vapor increases, thus forcing a 2°C per km increase in dew point.
  - (note: Because of the fluctuation in dew point temperatures in vertically moving air parcels, a more conservative measure of water vapor is the specific humidity (q) or the mixing ratio (w).

Adiabatic processes

- Adiabatic ascent
  - A rising parcel of unsaturated air will cool at the dry adiabatic rate of 10°C per km until the temperature reaches the dew point temperature. The dew point will experience a 2°C per km reduction too, so this must be factored into a calculation as to what level the temperature and dew point actually intersect.
  - From that point, both the temperature and the dew point will decrease at the saturation adiabatic rate. (The dew point CANNOT be greater than the temperature.)

Adiabatic processes

- Adiabatic descent
  - For a saturated parcel to descend and warm according to the saturation adiabatic rate, there must be water available for evaporation.
  - Once the excess liquid in the parcel has evaporated, the parcel will warm according to the dry adiabatic rate. The dew point will increase by 2°C per km due to an increase in water vapor partial pressure as the parcel sinks.

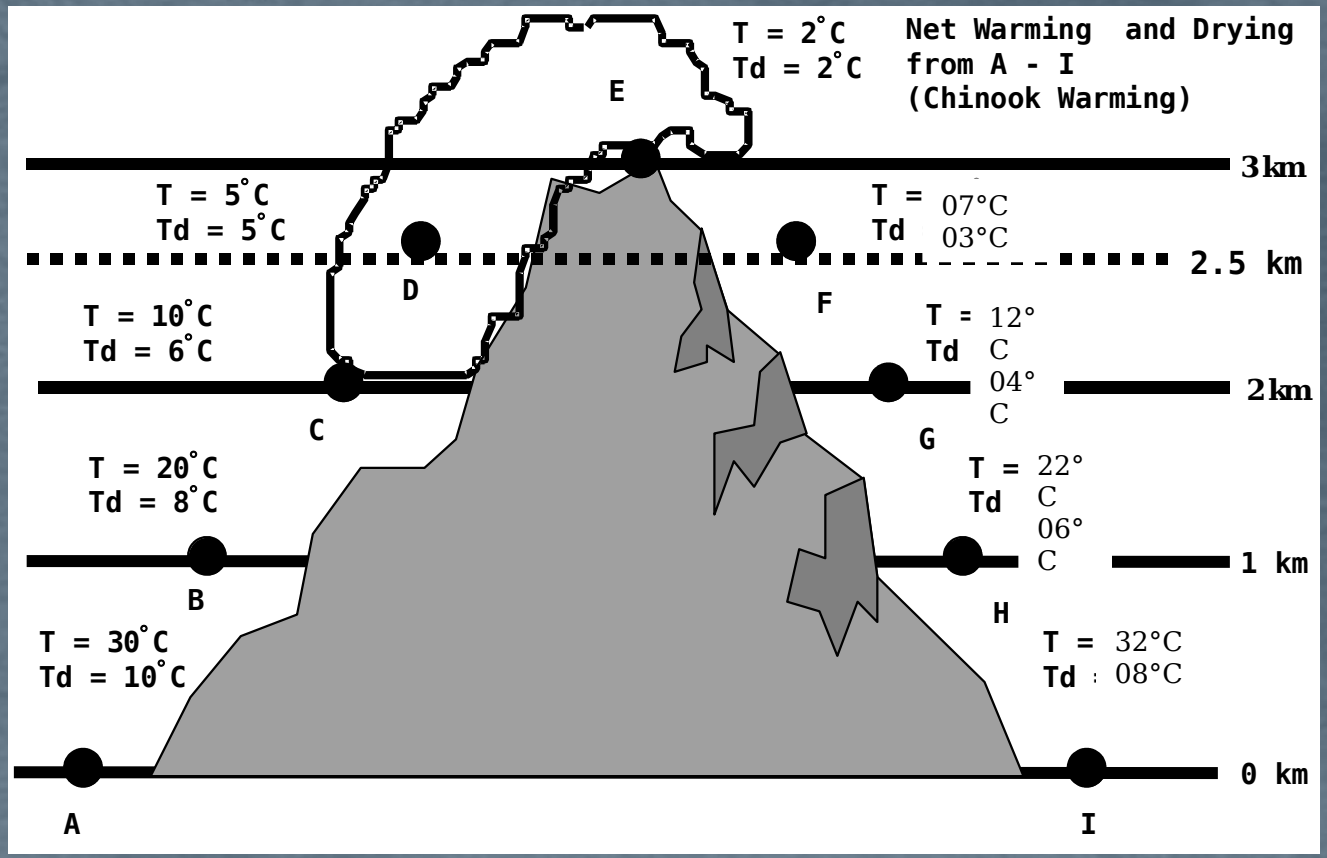
Adiabatic processes

- Adiabatic descent (cont)
  - A parcel of air descending at the saturation adiabatic rate warms more slowly than an unsaturated parcel.
    - Latent heat required to evaporate the water in the parcel is taken from the parcel air.
    - Results in a decrease in sensible heat of the parcel and thus a decrease in warming of the parcel.
    - Evaporation raises the dew point in unison with and equivalent to rises in the temperature.

Adiabatic processes

- Pseudo-adiabatic process
  - All condensed water/deposited ice which takes place during lift is assumed to precipitate out of the parcel.
  - Still, no heat is exchanged with the surrounding air (occurs in real life)

Pseudo Adiabatic Process



Adiabatic processes

- Pseudo-adiabatic process (cont)
  - The process is not completely adiabatic because mass (precipitation) is released to the environment (surrounding air or adjacent ground) (real life conditions). Thus, water vapor molecules are removed from the parcel via precipitation.
  - Heat released during condensation remains in the parcel and acts to warm it.
  - Pseudo Adiabatic ascent – a parcel of air is lifted dry adiabatically until it reaches saturation.

Adiabatic processes

- Pseudo-adiabatic process (cont)
  - Then it rises saturation adiabatically with both the temperature and dew point decreasing at the saturation adiabatic rate.
  - Pseudo adiabatic descent – sinking air warms at the dry adiabatic rate because there is no liquid water in the parcel to evaporate.

Adiabatic processes

- Potential Temperature (θ)
  - It is the temperature (K) that a parcel of air would have if it were brought dry adiabatically to the 1000 mb level.
  - Air moves along constant potential temperature surfaces (called isentropes) because, on the large scale, air motion is approximately adiabatic.

Adiabatic processes

- Potential Temperature (cont)
  - Potential temperature is conserved (remains a constant value)
  - Because potential temperature is conserved, it is useful for tracking air parcels, especially at frontal surfaces.
  - If you know the potential temperature of an air parcel at a given time, you can forecast the motion of the air parcel by moving it along the isentropes.
  - This concept is used in National Weather Service area forecast discussions.

Adiabatic processes

- Equivalent Potential Temperature (θ_e)
  - It is the temperature (K) that a parcel of air would have if it were lifted adiabatically until all moisture was precipitated out of the parcel, then brought dry adiabatically down to 1000 mb
  - The release of latent heat during the parcel's moist adiabatic ascent causes the parcel's equivalent potential temperature to be warmer than the same parcel's potential temperature. Note that θ and θ_e are equivalent for a completely dry parcel (i.e., a parcel without any water vapor)

Adiabatic processes

- θ_e combines the effect water vapor and temperature into one variable. As will be seen in Dynamics, θ_e is a very useful tool for identifying air mass boundaries (such as fronts) and for identifying available fuel for thunderstorms.

- Assign Review Exercise in WB-100
- Administer and evaluate Appraisal 102e and Written test at the end of the unit.